# MODELING OF BLOCK-BASED DSP SYSTEMS

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## ABSTRACT

Modeling semantics based on dataflow graphs are used widely in design tools for digital signal processing (DSP). This paper develops efficient techniques for representing and manipulating block-based operations in dataflow-based DSP design tools. In this context, a block refers to a finite-length sequence of data items, such as a sequence of speech samples, an image, or a group of video frames, as part of an enclosing data stream. We develop in this paper a meta-modeling technique called blocked dataflow (BLDF) for augmenting DSP design tools with more effective blocked data support in an efficient and general manner. We compare BLDF against alternative modeling approaches through a detailed case study of an MPEG 2 video encoder system.

## 1. INTRODUCTION

In the digital signal processing (DSP) domain, rapid prototyping tools based on coarse-grain dataflow semantics are widely used [2]. One important requirement in these tools is support for block-based processing, such as that involved in image and video applications. We develop in this paper a blocked dataflow (BLDF) modeling approach for efficient handling of block-based data in dataflow-based DSP design tools. BLDF combines meta-modeling, block-based processing, multidimensional representation, and dynamic parameter reconfiguration in a single, unified framework that leads to more efficient dataflow graphs for scheduling and software synthesis.

In this paper, by a dataflow model of computation (dataflow MoC), we mean a programming model based on dataflow semantics. Programs in a dataflow MoC are thus represented as directed graphs in which vertices, called dataflow actors, represent computational tasks, and edges represent logical FIFO communication channels between tasks.

A decidable dataflow model is one in which deadlock and unbounded buffer accumulation can be determined in finite time for every specification in the model. Examples of decidable dataflow models are CSDF [3], SDF [8], MDSDF [9] and SSDF [12]. For consistent specifications in each of these models, there is a unique, integer-valued repetitions vector that is indexed by the graph actors and gives the number of times each actor needs to be invoked to form a minimal periodic schedule for the graph.

A number of efforts have examined block processing at the level of individual actors. The objective in such vectorization is to improve throughput and reduce context-switching overhead by executing actors many times in succession. The scalable synchronous dataflow (SSDF) [12] model formalized this concept in the context of multirate dataflow graphs, and algorithms have been developed to extract the maximum vectorization potential from an SSDF graph [11]. More recently, retiming techniques have been explored for manipulating homogeneous dataflow graphs (graphs in which the production and consumption parameters are all equal to one) to improve vectorizability [6]. BLDF differs from these approaches in its applicability beyond the level of individual actors, and into arbitrary subsystems at any level of the modeling hierarchy. BLDF also differs in its close integration with parameterized dataflow semantics [1], which allows for powerful dynamic reconfiguration capabilities.

As dataflow modeling alternatives emerge further it is highly desirable to identify new modeling features that can be achieved through novel applications of existing models rather than defining a totally new dataflow variant for each new extension. This promotes reuse and integration rather than reinvention of the growing body of knowledge on established dataflow styles. BLDF adheres to this approach by defining general mechanisms that can be used to augment existing dataflow models with systematic data grouping capabilities. It is in this sense that we refer to BLDF as a meta-model. BLDF can be used with the well-known decidable dataflow models, SDF, CSDF, MDSDF, and SSDF, as described above. Its use with other, more dynamic models such as boolean dataflow [4] and SBF [5] may be possible, although efficient application to such models requires further investigation.

## 2. BLOCKED DATAFLOW

Blocked dataflow builds on parameterized dataflow semantics [1]. In a blocked dataflow subsystem, blocks of input data are treated as subsystem parameters, and the initialization graphs (the subinit or init graphs, as described below) are used in-between processing of successive blocks to change the value of the associated block-parameter. Thus successive blocks of data are translated into successive reconfigurations of block-parameter values.

For example, consider an image processing system that performs a given filtering operation on a stream of input images. A blocked dataflow representation might define the processing of a single image using a dataflow graph $G_c$. The graph $G_c$ operates on input from a special *image source* actor that is parameterized with an image $I$. The image source actor simply transfers its image parameter to its output according to the desired protocol. The transfer protocol involves both rasterization aspects, and may also involve *sub-blocking* (e.g., outputting the image as a sequence of row blocks). Such sub-blocking can be used to defined nested BLDF subsystems.

BLDF inherits most features of parameterized dataflow [1]. Thus, a BLDF specification (or subsystem) $\Phi$ also consists of three distinct graphs: 1) the *init* graph $\Phi$i; 2) the *subinit* graph $\Phi$s; and 3) the *body* graph $\Phi$b. Intuitively, the body graph models the main functional behavior of the subsystem, whereas the init and subinit graphs control the behavior of the body graph by appropriately configuring the body graph parameters. The init graph is invoked prior to each invocation of the associated (hierarchical) parent subsystem, $\mathrm{parent}(\Phi)$, while the subinit graph is invoked prior to each invocation of the associated body subsystem $\Phi$b, thus allowing for two distinct "frequency levels" of reconfiguration control [1].

## 2.1 Iteration control

The major enhancement in BLDF is the delivery method of data tokens into body graphs. In BLDF, blocked data tokens such as sequential MPEG2 video streams are delivered via the parameter value updating process of init or subinit graphs so that an init or a subinit graph can extract information concerned for the associated body graph from raw data tokens delivered, and then convert raw data tokens as well as the information extracted into sets of new parameter values for the body graph. Thus, raw data tokens are delivered to the associated body graph as parameters along with other parameters extracted from them before the body graph starts running.

Figure 1 shows the mechanism by which BLDF builds on parameterized dataflow semantics.

Since the body graph of Figure 1(a) takes image frames directly from the outside without any parameterization process within an init or subinit graph, it is not possible to extract important information such as iterations of the associated body graph and also not possible to define detailed operation of each actor within that body graph by setting iteration limits.

On the other hand, in a Figure 1(b), image frames are transferred to the subinit graph and then converted into a block of parameters, which are set as parameters of each relevant actor in the associated body graph. Figure 1(b) allows dynamic configuration of parameters for the associated body graph such as image resolution and block size as basic processing units along with other provisional parameters at the stage of the subinit graph, which directs detailed operation of the associated body graph before that body graph starts an invocation of itself.

At the same time, iterations of each actor within a body graph can be obtained along with other parameters. Suppose, for example, that an init or a subinit graph takes a $\boldsymbol{Z}$ pixel frame from its input port. An init or a subinit graph can obtain $\boldsymbol{Z / N^2}$ iterations of the associated body graph actor by setting the *block size* parameter for the body graph as $\boldsymbol{N}$ by which image frames are divided into sub-image frames. Each actor within the body graph then operates on the basis of sub-image frames for high throughput and more parallelism. Iteration numbers may be used further as factors in a quasi-static looped schedule by a BLDF scheduler. Obtaining parameters relevant to the scheduling of the associated body graph before it runs and reconfiguring those parameters dynamically based on concerned payloads of tokens delivered at a runtime gives an application developer enhanced flexibility and efficiency in the design phase.

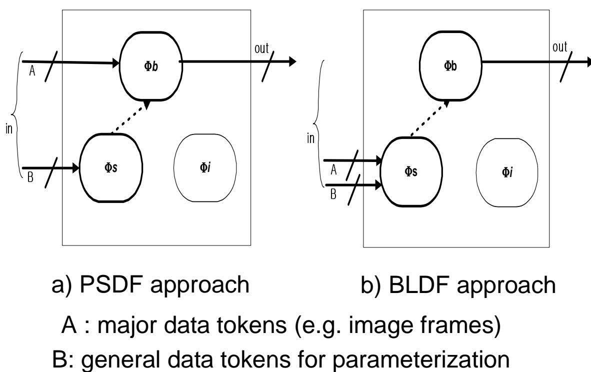



**Figure 1.** PSDF and BLDF.

## 2.2 Token delivery

One of the advantages of BLDF is its efficiency in token delivery. First, in token delivery, BLDF enables us to reduce buffers required for delivering tokens among actors. This is because tokens can be delivered from parent graphs to nested body graphs by parameterization. Figure 2 shows how BLDF reduces buffering requirements in this way. In Figure 2, the "D" actor requires both "a" and "b" tokens, while the "A", "B" and "C" actors require only token "a". Here, suppose also that a sample rate change from "A" to "D" exists in the specification. Then in Figure 2(a), "A" , "B" and "C" actors must have additional input/output ports only for delivering token "b" to "D" without sample rate inconsistency. This in turn causes "redundant" or "extra" buffers between intermediate actors. However, in Figure 2(b), the subinit graph Φs converts input data into two parameters "a" and "b", and then token "a" is set to actor "A" as a parameter while token "b" is set to the actor "D" directly as a parameter, while maintaining sample rate consistency. This parameterization process enables us to remove redundant connections and buffers between actors in BLDF.

## 2.3 Data tokens with nested headers

Most multimedia data tokens consist of a *header* part and a *payload* part. The header part has the information for handling the payload. However, the payload also may have sub-header and sub-payload components. Therefore, each level of composite actors implemented hierarchically or heterogeneously may process a different area of a packetized multimedia data token. BLDF provides an efficient way for delivering data tokens to composite actors of lower hierarchical levels by parameterization. Only the relevant part needs to be decoded for configuration and the remaining parts can be encapsulated as parameters for composite actors of lower hierarchical levels in the dataflow specification. Figure 3 shows how data tokens with nested headers can be handled in BLDF. Decoding headers sequentially according to the need for the associated header information allows us to implement each module within an application consistently, which is easy to understand for future code reuse. This approach also reduces the number of connections and buffers required between actors by parameterization.

# 3. APPLICATION EXAMPLE

## 3.1 Brief review of MPEG2 video streams

The MPEG2 specification has been widely selected as a standard for coding/decoding moving picture frames. Therefore, many modern embedded systems handling multi media integrate MPEG2 decoders. This paper has selected MPEG2 as one example of a real field application for an embedded system. The MPEG2

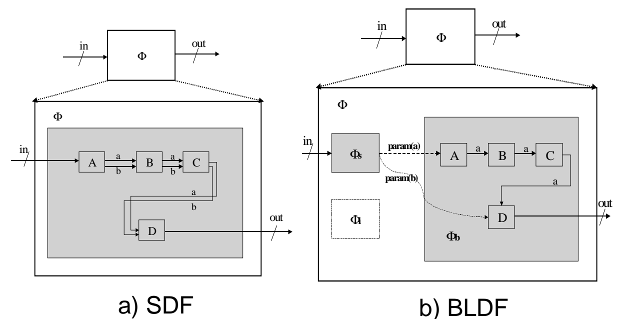



**Figure 2.** BLDF and SDF: **param() : parameterization; Φs : subinit graph, Φb: body graph; "a", "b" : tokens being delivered.**

specification roughly consists of three parts: the video, audio and system parts. In this paper, we focus on the video part to show differences in efficiency, flexibility and extensibility among alternative modeling formats.

Moving pictures are made from combinations of consecutive image frames. Each image frame is composed of pixels and each pixel has its own value representing the degree of RGB or YCrCb. Pixel values are not independent but are correlated with their neighbors. Therefore, the value of a pixel is predictable, given the values of neighboring pixels. Image frames usually have redundant information in view of image compression, which can be categorized into two redundancies: spatial redundancy and temporal redundancy, based on whether they are exploited in relation with neighboring frames or not. Spatial redundancy is redundant information lying in an intra frame while temporal redundancy is redundant information lying between inter-frames.

The MPEG2 specification separates image frames into three different types (I, P and B frames). I frames exploit only spatial redundancy, while P and B frames exploit both spatial redundancy and temporal redundancy. Thus, an I frame does not refer to neighboring image frames for reducing redundant information within itself and plays a role of an anchor frame to separate groups of pictures from continuous image frames.

Even though the P and the B frames exploit both spatial redundancy and temporal redundancy, there are different features between P and B frames in view of control flow. The P frame reduces redundant information by referring to a previous I or P image frame as a reference frame, differentiating pixel values between the current P frame and the reference frame, and exploiting spatial redundancy like the I frame. In contrast, the B frame requires two reference frames (a previous I or P frame and a future I or P frame) as reference frames for reducing temporal redundancy. The difference in the number of reference frames required among frame types makes it difficult to express an MPEG2 encoder in pure SDF form.

### 3.2 Problems in design of an MPEG video encoder with SDF

The problems from designing an MPEG2 video encoder using only SDF semantics occur from the dynamic change in MPEG2 video streams. Some actors inside the MPEG2 encoder dynamically change their operation based on the content of data tokens being delivered to them while other actors maintain their operation consistently. Also, motion compensation demands that image frames are encoded in different sequences from sequences transferred to the encoder. More specifically, problems in designing an MPEG2 video encoder under SDF are as follows.

- P1. *Control problem*. Every actor under SDF must consume and produce at least one token, which means that every connection between actors has to deliver at least one token during one invocation of the enclosing system. However, it is possible that some actors need special tokens from their input ports only in special cases and in other cases do not need any token. This situation arises in actors of an MPEG2 video encoder.
- P2. *Consistent schedule problem.* Data tokens can be categorized into two sub-classes: major data tokens every actor is concerned with, and additional data tokens that are relevant for proper subsets of actors. Some actors of an MPEG2 video encoder require additional input or output ports that are only for delivering additional tokens. Those tokens have features of parameters and are usually used for setting internal state of actors. With such additional input or output ports only for delivering tokens to other actors, as the layout of applications get more and more complex, the possibility of introducing sample rate inconsistency into the dataflow signal processing increases. SPDF (Synchronous Piggybacked Data Flow) [10] suggested a piggybacked way to solve this problem. However, [10] also cannot avoid unnecessary and redundant delivery of the information, even if the methods of [10] are used to reduce buffers required by a piggybacked way, which delivers only a pointer of an entry in the global state table.
- P3. *Iteration counts.* Obtaining actor iteration counts at a compile time is a major advantage in SDF. It reduces overhead of scheduling problems at a runtime. However, in general, the invocations of each actor can vary dynamically based on data being delivered. Such scenarios are not handled by SDF.

Also, an application developer may wish to manually set or dynamically change iteration numbers of special actors for low power requirements or quick user response time, which will affect iteration counts of subsequent actors. Such situations are also not permitted in SDF.

However, in BLDF, iteration numbers of subsequent actors can be determined at the “init” or “subinit” stage by extracting corresponding information from data tokens delivered and reconfiguring the associated parameters, while allowing for low overhead quasi-static scheduling, as in parameterized dataflow [1]. This is possible through blocked parameter delivery in BLDF, which takes a block of input tokens, e.g. image frames at the init or subinit stage, and then converts them as blocked parameters along with other parameters. At the same time, important configuration information such as the resolution of an image frame and basic processing unit size (block size) can be used for dynamically calculating iteration counts of relevant actors in the associated body graph.

- P4. *Saving buffers and reducing unnecessary delivery.* BLDF allows us to optimize data token delivery by “parameterization”. By “parameterization”, low overhead, “low frequency” connections between actors can be used. As mentioned in **P2,** we have two kinds of data tokens: tokens every actor requires and tokens that are relevant for individual actors. The second type of tokens can be directly delivered to the associated actors by parameter settings processed at the init or subinit stage. This allows us to remove unnecessary data delivery as well as unnecessary buffering requirements, as will be demonstrated in Section 4.

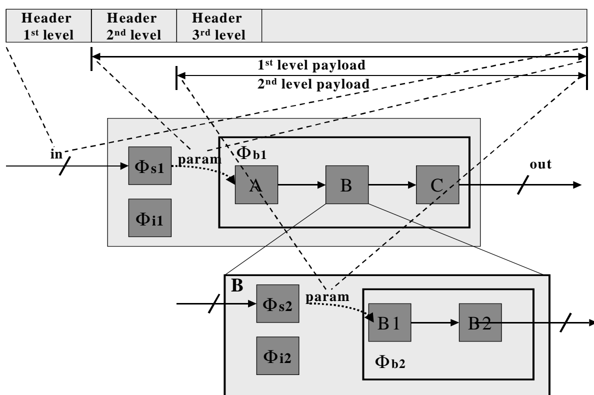



**Figure 3.** Data tokens with nested headers.

## 4. EXPERIMENTS

We have prototyped a preliminary version of BLDF semantics in Ptolemy II [7], a widely-used tool for developing and integrating models of computation.

## 4.1 MPEG2 Video encoder implementation

We have implemented an MPEG2 Video encoder under the Ptolemy II environment in three different ways, including using BLDF, and have compared the resulting models in efficiency and flexibility.

*Method 1. FSM and SDF combination*

An application developer often considers FSMs (Finite State Machines) when designing an application with nontrivial control flow. An MPEG video encoder clearly has features of dataflow, along with nontrivial control flow. In this method of implementation, we have used the two combined models of computation, SDF and FSM, in a heterogeneous and hierarchical way, using the heterogeneous modeling capabilities of Ptolemy II. Figure 4 illustrates our resulting design.

Our FSM representation within the MPEG2 video encoder has three states where each state is refined to three different SDF subgraphs, depending on the type of image frame: I, P or B. Since an I frame is coded by exploiting only spatial redundancy, the SDF graph shown in figure 4(c) for I frame processing does not have a motion compensator module. The SDF graph shown in figure 4(d) for P frame processing, which refers to only a previous I or P frame, has one motion compensator module, while the SDF graph shown in figure 4(e) for B frame processing, which refers to both a previous and a future I or P frame, has two motion compensator modules.

Here, it is useful to focus on two special functional blocks: *MPEGQuantizer* and *ReferenceFrame,* which help to distinguish our alternative encoder implementations.

*MPEGQuantizer.* This block needs a picture ID token to identify what image frames are delivered to it. MPEGQuantizer is placed after several preceding actors that are not concerned about the picture ID token. In implementation method 1 and method 2 (introduced below), the picture ID token must go through all preceding actors to the target actor, MPEGQuantizer, which, due to sample rate changes through the preceding actors, consumes that token to avoid an inconsistent schedule.

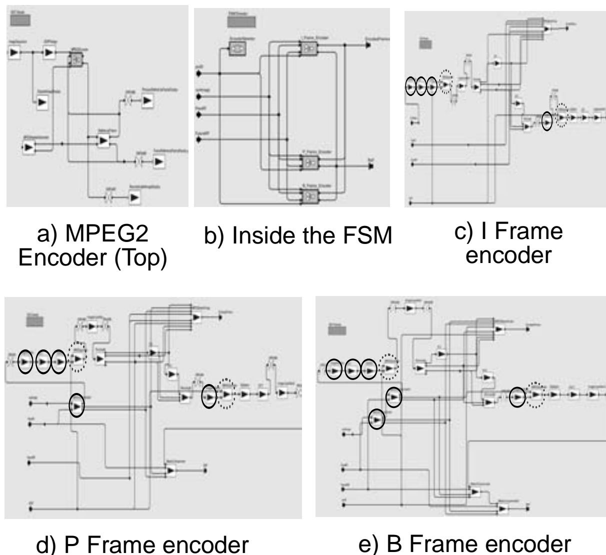
*ReferenceFrame*. This block operates differently, depending on the type of image frame delivered, and uses dummy tokens with "0" values:

Case 1: When an I frame comes, ReferenceFrame produces "0" values to output ports both for a previous and for a future reference frame. This is because an I image frame does not perform motion compensation. ReferenceFrame consumes I frame from its input port and updates its reference frame with the "I" frame. Here, ReferenceFrame has initial tokens as with a *delay* actor, for it is connected within a feedback loop.

Case 2: When a P frame comes, ReferenceFrame produces a previous I or P frame, which was saved in a previous cycle, for the previous reference frame and a "0" value for the future reference frame. Like when an I frame ID comes, a P frame is also saved as a reference frame inside of ReferenceFrame.

Case 3: When a B frame comes, ReferenceFrame produces two saved reference frames (P and I frames) to the output ports. However, since a B frame is not used as a reference frame, it is discarded and not used for updating reference frames inside of ReferenceFrame.

In summary, this implementation method (Method 1) can satisfy problem P1; however, P2, P3 and P4 remain unsolved.


a) MPEG2 Encoder (Top) b) Inside the FSM c) I Frame encoder

d) P Frame encoder e) B Frame encoder

**Figure 4.** FSM and SDF Combination

*Method 2. SDF*

In this method, we have implemented an MPEG2 Video encoder without integrating the FSM model of computation. All functional blocks inside are same as the method 1. However, method 2 does not have separated I, P and B sub-encoders so that all image frames go through two motion compensators with real values or dummy values depending upon the image frames. This implementation simplifies the design of an MPEG2 Video encoder. However, it still has the same problems (P2, P3 and P4) unsolved, as with method 1.

*Method 3. BLDF*

In this method, we separate the functional blocks of an MPEG2 video encoder into two parts: a subinit and a body graph. The actors configuring the body subsystem are placed in the subinit graph, and the actors actually processing image frames are placed in the body subsystem. First, the subinit graph obtains information required for configuring a body subsystem from data tokens delivered to itself and then converts image data tokens, themselves, into blocked parameters for the body subsystem along with other parameters, such as block size and picture ID, obtained from image data tokens.

In parameterized dataflow, blocked data tokens such as image frames directly go to a body graph. An init or subinit graph manipulates only data tokens with parameter features for a body subsystem. Therefore, an init or subinit graph can not obtain parameters such as image resolution or block size for manipulating iteration numbers of the actors in the associated "body" graph.

Early knowledge of the iteration count of each functional block for a body subsystem gives more efficiency and flexibility in manipulating and predicting actors of the associated body graph. Above all, an iteration count acts as a factor in a looped schedule of quasi-static scheduling in BLDF. Thus, a more efficient quasi-static schedule of the associated body graph can be established, while keeping much of the advantage (the predictability) of SDF in the schedule. The name of BLDF is originates from this feature that a block of data tokens is packaged as parameters and then delivered to the associated body subsystem. Blocked data token delivery of BLDF enables us to reduce dimensions of MDSDF [9] by processing multi dimensional data tokens dimension by dimension with blocked data processing of nested BLDF subsystems. At the same time, BLDF can be used in conjunction with MDSDF, with BLDF parameter control used to define the boundaries of pro-

cessing to be performed using MDSDF semantics.

Figure 5 shows iteration counts of the functional blocks in the associated body subsystem and how iteration counts are used for factors in a looped quasi-static schedule of the MPEG2 video encoder application. Here, the init subsystem contains the following three actors.

*ImageFrameParameterizer.* This actor delivers image frames to the ImagePropagator actor of the body subsystem as BLDF parameter values.

*MPEGHeaderGenreator.* This actor generates a picture ID for the associated body subsystem. The parameterized token delivery of a picture ID relieves the associated body graph of a complicated meshed layout of an MPEG2 video encoder and the inconsistent scheduling problem (P2).

*BlockSize.* This actor sets a block size parameter value for the associated body subsystem, which is the basic processing unit by which a full image frame is divided into groups of sub images for high throughput and more parallelism. Each functional block in the associated body subsystem processes an image frame on the basis of sub images defined in this manner.

In the body subsystem, it is useful to focus on two functional blocks: the *MPEGQuantizer* and *ReferenceFrame*. These two actors have additional input ports for a picture ID token in methods 1 and 2, but in BLDF, no additional input port for a picture ID token is required any longer since the tokens are delivered to these actors as parameters, not tokens. The parameterized token delivery simplifies the layout of the MPEG2 video encoder and also removes redundant connections between all preceding actors to the target actor actually consuming that information without inconsistent schedule problem.

Also, this method allows dynamic configuration of parameters at a runtime. The subinit graph analyzes the tokens delivered to itself and then sets parameters of the associated body subsystem based on runtime need for parameter value delivery. Parameters maintain their value consistently during one iteration of the associated "body" graph. Figure 6 shows our implementation of the MPEG2 video encoder application under BLDF.

## 4.2 Comparison

Method 1 (FSM + SDF Combination) has three different SDF graphs to which three states of the FSM are refined. However, each refined SDF graph shares most of its actors with other refined graphs, so there is a problem with redundant copies of actors among each refined SDF graph.

**Figure 5.** Blocked data delivery in BLDF

Method 2 (SDF) simplifies three sub-encoders within method 1 into one common encoder. Thus, method 2 removes the problem of redundant (duplicated) actors. However, it still has problems of P2, P3 and P4 unsolved. Thus, unnecessary connections for picture ID delivery need to be established through preceding actors, most of which don't need a picture ID, in order to avoid an inconsistent schedule when the sample rate of tokens changes.

Method 3 (BLDF) has a similar layout as method 2, except that connections for delivering the picture ID are removed due to parameterized token delivery. This makes the layout of the encoder much simpler than method 2. Besides this, since parameters of the body subsystem are dynamically set by the subinit graph, method 3 provides more flexibility and extensibility in the design and maintenance of the application, especially by making room for future changes of the specification, along with improved efficiency in the design by reducing connections between functional blocks.

To illustrate this efficiency advantage, the following table shows how many buffers and connections in BLDF can be saved as the application complexity increases. In the MPEG2 application, we have two actors named MPEGQuantizer and InverseMPEGquantizer that require additional tokens for internal setting of values. The number of connections and the number of buffers required can be calculated by multiplying the number of preceding actors and the number of tokens for parameters.

Number of preceding actors : $n$
Number of tokens for parameters : $m$
Number of connections : $n*m$
Number of buffers required : $n*m$

Therefore, generally, $n*m$ unnecessary connections and buffers between preceding actors can be saved in BLDF, compared with alternative modeling formats.

# 5. CONCLUSIONS

This paper has developed a blocked dataflow (BLDF) modeling semantics for augmenting dataflow-based DSP design tools with integrated capabilities for meta-modeling, block-based processing, multidimensional representation, and dynamic parameter reconfiguration. BLDF builds on parameterized dataflow semantics, and is

a) MPEG2 Encoder in BLDF (Top) b) "subinit" graph

c) "body" graph

**Figure 6.** MPEG2 Encoder under BLDF

compatible with decidable dataflow models such as CSDF, MDSDF, SDF, and SSDF. This paper has described the semantics of BLDF, and illustrated its efficiency through a case study of an MPEG 2 video encoder system. Useful directions for further study include optimized synthesis, hardware/software partitioning algorithms, and automated verification from BLDF specifications.


## ACKNOWLEDGEMENTS

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Table 1. Comparison of three methods in "Buffer memory" and "Token delivery"

| | **Total**<br><br>***#B***: Number of buffers required<br>***#W*** : Number of words required<br>***#W* = *#B* * *#WpB***<br>***#WpB*** : Number of words per buffer<br>cf) *Picture ID* : 1 word per buffer is required.(***#WpB* = 1**) | "MPEGQuantizer" actor<br>< # of preceding actors ><br>SDF+FSM : 3(I), 4(P), 5(B)<br>SDF, BLDF : 5<br># of tokens for parameters : 1 | | "Inverse MPEGQuantizer" actor<br># of preceding actors : 1<br># of tokens for parameters : 1 | |
|---|---|---|---|---|---|
| | | Number of connections | Number of buffers required | Number of connections | Number of buffers required |
| SDF + FSM | ***#B*** :<br>= (3+4+5)+(1+1+1)<br>= **15 buffers**<br><br>***#W*** = *#B* * *#WpB* :<br>=15 * 1 = **15 words** | I subencoder:<br>= 3*1 = **3**<br>P subencoder:<br>= 4*1 = **4**<br>B subencoder:<br>= 5*1 = **5** | I subencoder :<br>= 3*1 = **3**<br>P subencoder :<br>= 4*1 = **4**<br>B subencoder :<br>= 5*1 = **5** | I subencoder :<br>= 1*1 = **1**<br>P subencoder :<br>= 1*1 = **1**<br>B subencoder :<br>= 1*1 = **1** | I subencoder :<br>= 1*1 = **1**<br>P subencoder :<br>= 1*1 = **1**<br>B subencoder :<br>= 1*1 = **1** |
| SDF | ***#B*** :<br>= (5)+(1) = **6 buffers**<br>***#W*** = *#B* * *#WpB* :<br>= 6 * 1 = **6 words** | 5*1 = **5** | 5*1 = **5** | 1*1 = **1** | 1*1 = **1** |
| BLDF | ***#B*** : **0 buffers**<br>***#W*** : **0 words** | **0** | **0** | **0** | **0** |